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Energy, exergy and thermo-economic analysis of solar distillation systems: A review

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ABSTRACT

Desalinated water, the final product of a solar distillation system, is useful for drinking purpose, community services, industry and agriculture on a small scale. It is expensive and may be considered as an industrial product. In the present communication, it has been tried to collect information about the ongoing research activities in the field of solar distillation system with the aim to enhance productivity and efficiency through an effective thermodynamic tool i.e. energy and exergy analysis, especially of the solar stills, similar to its wide application in complex thermal systems such as steam or gas turbine, boiler and cogeneration systems. Thermodynamic models for the energy and exergy analysis have been presented based on the fundamental heat transfer correlations in literatures for the simple basin type solar stills. Energy efficiency and productivity of the conventional solar stills is found to be low in the range of 20–46% and less than 6 L/m^2/day, respectively, for most cases, even under optimized operating conditions. The exergetic efficiencies are estimated to be between 19% and 26% for a triple effect system, 17–20% for a double effect system, and less than 5% for a single effect system. Productivity increases significantly by the use of integrated solar stills with better efficiency. The overall energy and exergy efficiency of the integrated systems rises up to 62% and 8.5%, respectively, using single effect solar stills. An attempt has also been made to review works on economic and thermo-economic analysis of solar stills. The cost of desalination through solar stills is reported in the range of US$0.014 to 0.237/L. It decreases further with increase in efficiency. It is observed that integrated solar desalination systems and technologies will be better choice than the conventional solar distillation systems for rural as well as urban areas blessed with sufficient sunshine.

Contents

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1. Introduction

Energy is precious. There is strong relationship between energy consumption and national wealth. The progress of modern society is inextricably linked to our ability to harness an increasing number of forms of energy on an increasing scale. Humankind currently uses 410 × 1018 J (equivalent to over 90,000 billion litres of oil) of commercially traded energy per annum [1]. Energy scarcity due to unplanned exploitation of existing reserve of the fossil fuels and consequent damage to the environment is a global problem. It is the duty of every individual to preserve it and save it. By the use of energy for overall development, forms of energy are changing in quantity and at the same time, it is degraded in quality. The most effective way to meet the energy demand and conservation of energy is to use energy more efficiently. Energy and exergy analysis of any energy system and or components of the system are a well established and effective tool of thermodynamics for conservation, auditing and accounting of the energy in terms of quantity as well as quality [2–5].

Fresh drinking water is one of the most significant and fundamental factor of vital importance other than energy and food. It determines and drives the economics and consequently the way of life in a society. Shortage of drinking water is one of the major problems faced by all over the world especially in arid remote areas together with the present growing concern of energy crisis, global warming and the climate change. Approximately 70% of earth′s surface is covered by water, but 97% of the water is saline and in the ocean, only 0.62% of the available water is in the form that can be traditionally treated for human consumption. Since the last century, these drinking water sources from both surface and ground water resources have been increasingly depleted due to increase in worldwide population, pollution, over-exploitation, rise in the salinity level of water because of insufficient rainfall and inadequate management of the water resources [6–8]. One study of water shortage trends estimates that of the approximately 7 billion people living on the earth, 400 million people now live in the areas where there is acute scarcity of drinking water, and this number may grow to four billion by mid-century [9]. The year "2003" was declared as the "UN International Year of Freshwater" by the United Nations, in an effort to act and solve the water related problems. The demand of fresh drinking water is increased by six-fold with respect to three-fold increase in the world′s population. It is well established fact that 80% of the world′s illness and 50% of total infantile death is directly related with the shortage of good quality potable water [10,11].

There is dire need to develop suitable technologies for safe drinking water, production and supply to the humankind. High quality irrigation system also requires fresh water to be mixed with available saline water to make its quality to an acceptable level, especially in the greenhouse crop farming. Sometimes, surface and ground water resources are found to be contaminated with heavy metals such as Arsenic, Cadmium, Mercury, Lead and other salts beyond the permissible limit which causes health problems. Even in the course of transportation of fresh water through various means, there is a chance of adulteration of water. Therefore, it has become necessary to desalinate saline water with the help of renewable energy sources locally by developing suitable technologies of higher energy efficiency for safe drinking water at a reasonable cost. Solar energy is one of the best promising options among the renewable energy sources which are abundantly available. Widespread use of solar energy for desalination will be attractive even in the developed countries giving much importance to reduce the amount of greenhouse gas emissions to the environment causing global warming and climate change due to present accelerating rate of utilization of fossil fuel-based energy [12].

This paper presents a comprehensive survey and review of the efforts made in solar distillation systems and technologies with focus on the energy and exergy efficiency of the system. Brief thermodynamic models for energy and exergy analysis are presented. The research activities on the techno-economic and usual economic analysis related with solar distillation systems are also highlighted here. The theoretical as well as experimental efforts made towards enhancing the productivity, energy and exergy efficiency of the solar distillation systems are given with the aim to encourage further research and development in this direction.

2. Desalination technologies and solar distillation systems

Desalination technologies are not new in the world. Conventional desalination processes based on distillation and involving phase change are multistage flash (MSF), multi-effect distillation (MED) and vapor compression (VC) distillation. On the other hand, membrane processes such as reverse osmosis (RO) and electrodialysis (ED) do not involve phase change. These desalination technologies are established but consume fossil fuels based high grade energy. MSF and RO processes are widely used worldwide: 44% and 42% of the world desalination applications, respectively. Among all these processes, RO has the lowest energy consumption [13]. More than 90% of the worldwide installed sea water desalination capacity is based on distillation process. One of the main advantages of the distillation process is that it requires heat only up to 120 °C which can be supplied from solar energy or other renewable energy sources [14]. Recently, considerable attention has been given to the use of renewable energies, especially solar energy as an alternate energy source for desalination due to increasing cost of fossil fuels based energy. There are other valid factors to shift in policy for using solar energy in place of conventional sources of energy such as un-even distribution of energy in remote areas, chances of depletion of conventional sources of energy due to fast rate of consumption, need of sustainable and pollution free environment and political risks of nuclear energy. However, there are evidences in history about the use of solar energy for getting fresh drinking water since the evolution of civilization [10,15].

Solar energy is found to be the most suitable to supply the required energy for a desalination process either in the form of thermal energy, mechanical energy or electrical energy. The solar distillation systems has been studied, designed and being used worldwide. The solar distillation systems are primarily categorized as passive and active system [16]. The most conveniently used solar distillation system consist of simple passive solar stills shown in Figs. 1 and 2, where the heat collection and distillation process take place within the same equipment. It is simple in design and easier in fabrication at lower cost. The active solar distillation system shown in Fig. 3 comprises of an additional source of

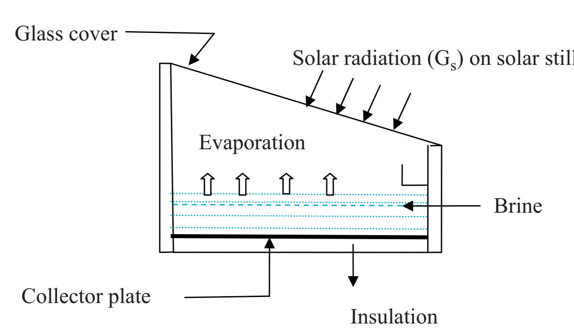

Fig. 1. The schematic view of a single effect single slope basin type conventional passive solar still [12].

feeding the thermal energy into the basin of passive solar still to increase the evaporation rate and continue the distillation even in the absence of solar radiation. The additional means may be solar collectors, solar ponds or waste heat available from various industries or power plants.

The ultimate objective of any solar distillation system is to maximize distillate output. The distillate output from a solar still depends upon various factors like climatic parameters such as solar insolation, ambient air temperature, wind velocity, humidity of the atmosphere, sky conditions etc. and design parameters such as thermo physical properties of the material used in its fabrication, orientation of still, tilt angle of cover, spacing between cover and water surface, insulation of the basin, vapor leakage from still, absorption-transmittance properties of still, etc. and operating parameters such as water depth in the basin, temperature of the feed water, salinity of water, etc. [14]. A large number of theoretical as well as experimental research papers published by the researchers from all over the world are available on the various aspects of solar distillation systems. A very comprehensive review of literature on all aspects of solar distillation has been provided by Talbert et al. [17]. An overall review and technical assessments of various passive and active solar distillation systems development in India is presented by Arjunan et al. [18]. Kaushal and Varun [19] have reviewed and compared different types of solar still including its geometries. A detailed review of different studies on active solar distillation system over the years by Sampathkumar et al. [20] summarizes the recent research works carried out in the areas of different types of solar stills especially thermal modeling, parametric study, and presented a comparative study of active solar stills in tabular form including the schematic diagrams of various types of solar distillation systems. Tiwari and Tiwari [16] have presented a wide coverage of the recent advancement in solar distillation related studies, analysis, results in the literature including their own extensive research works carried out and published in the field of solar stills. The basic heat and mass transfer relation responsible for developing, testing procedure for various designs of solar stills have also been discussed. It is recommended that the double slope fiber re-in forced plastic (FRP) conventional solar still is the most economical solar still to provide drinking water for domestic applications at decentralized

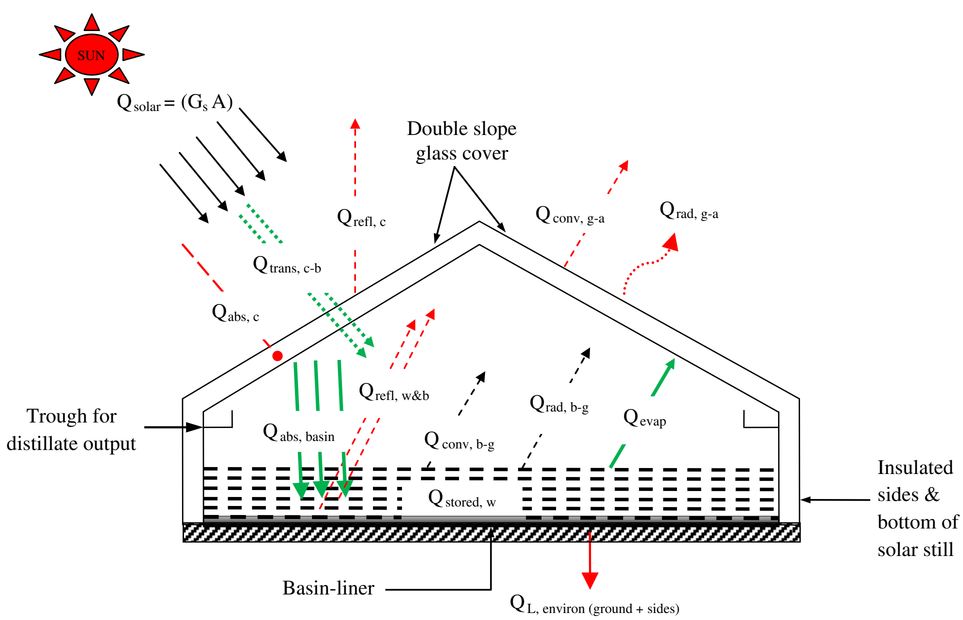

Fig. 2. The major energy transfer mechanism in a single effect double slope basin type conventional solar still.

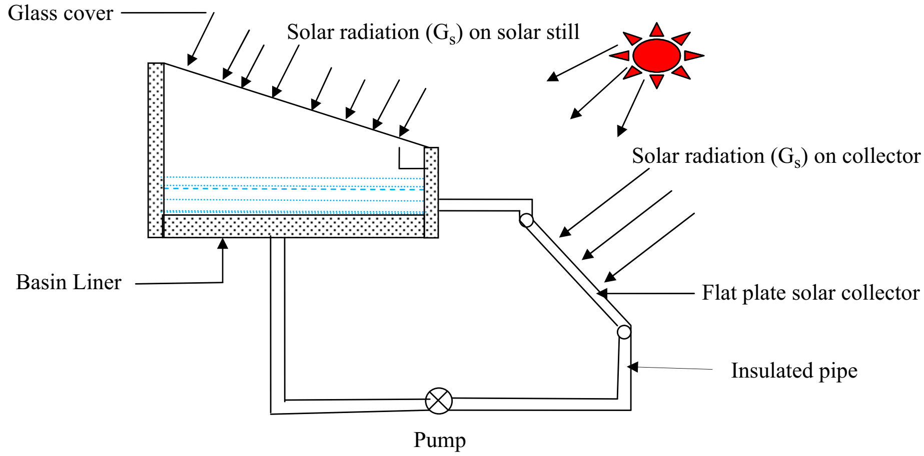

Fig. 3. An active solar still integrated with a flat plate solar collector.

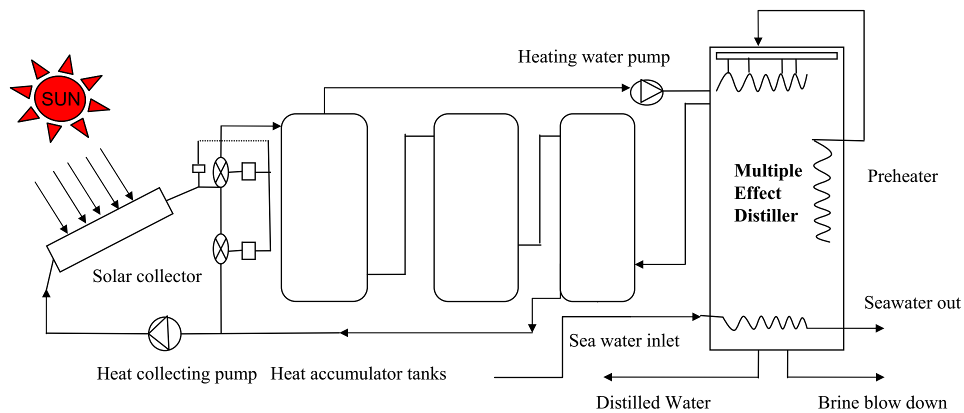

Fig. 4. A simplified diagram of the Abu Dhabi Solar Desalination Plant [21].

level. The active solar still is more suitable for economical applications like distilled water for selling purposes, extraction of essence from different seeds and green leaves etc., use in batteries, chemical laboratories, etc.

Success story of Abu Dhabi, UAE solar desalination test plant of pure water production capacity of 80 m^3/day (a yearly average value) operated successfully for 18 years till June 2002 has been described by Nashar and Ali [21]. A simplified schematic of the solar distillation plant is shown in Fig. 4. It has worked on a multiple effect distillation (MED) principle of solar distillation. The plant has proved its technical feasibility and proved to be reliable in operation with few minor maintenance problems. It is concluded that the cost of water from solar MED plants is competitive with that from a conventional MED plant if the rising trend of fossil fuel cost is taken into account. Since 2009, about 30 small-scale desalination plants are running in Abu Dhabi. Each system has a capacity to produce about 60 m^3 of freshwater daily. The plants rely on groundwater, with a salinity of about 35,000 ppm (parts per million) – a little less than local sea water – as a source for the desalination process. Each plant has an array of solar photovoltaic panels to produce the electricity necessary to pump groundwater to the surface and then pressurize it and run it through a special membrane capable of removing most of the dissolved salts. Recently, Abu Dhabi has constructed 22 eco-friendly solar desalination plants that will generate 1050 kWh of clean energy and 6600 gallons of clean water per day. There is plan to build a large-scale, commercially viable water-desalination plant powered through renewable energy by 2020 [22]. Environment Agency of Abu Dhabi is also testing a new solar energy desalination system which will be more eco-friendly, as well as less costly. A number of research works are going on to produce drinking water based on solar energy and other renewable energy sources in Saudi Arabia.

Similarly, the solar distillation plants have been installed and operated successfully on commercial scale in many countries like India, Pakistan, Israel, Mexico, Spain, Australia, USA, etc. [16]. These experiences encourage us to revive the solar distillation technologies with improved design for higher productivity and efficiency at competitive cost. To achieve this goal, thermodynamic analysis based on energy and exergy analysis is found to be the appropriate method which can be applied for the process and system improvement.

3. Thermodynamic analysis

Thermodynamic analysis is an essential tool for system design, analysis, and optimization of any thermal system. Any analysis of solar thermal system will be incomplete and inadequate without looking at it from the thermodynamic point of view. The primary objective in the design and optimization of solar distillation process is to utilize maximum available solar energy restricting the heat losses from the system to a minimum thermodynamic level for the maximum output (distilled water) in quantity and qualities i.e. maximize still productivity. Quantity and quality of the energy transfer as well as mass transfer should be investigated throughout the distillation processes. Therefore, a thorough analysis of the convection and radiation process should be based on the mass and energy conservation principles including the quality aspect of energy, i.e. exergy balance of the process [2,23,24].

3.1. The first law analysis: energy analysis

Energy analysis is based on the first law of thermodynamics, which is based on the conservation principle of energy in quantity. Energy balance equation for steady flow process of an open system is given by [25],

$$\sum \boldsymbol{E_i} + \sum_{j=1}^{n} \boldsymbol{Q_j} = \sum \boldsymbol{E_O} + \boldsymbol{W_{net}} \tag{1}$$

where, $\boldsymbol{E_i}$ and $\boldsymbol{E_O}$ are the quantity of energy associated with mass entering and leaving the system, respectively. $\boldsymbol{Q_j}$ is the quantity of heat transferred to the system from source at $\boldsymbol{T_j}$ and $\boldsymbol{W_{net}}$ is the net work output of the system.

The energy or first law efficiency, η_e, of a system or system components is defined as the ratio of energy output to the energy input of system or system components i.e.

$$\eta_e = \frac{\text{Desired output energy}}{\text{Input energy}} \tag{2}$$

3.2. The second law analysis: Exergy analysis

It is the second law of thermodynamics, which provides insight into optimum means of using energy to perform a given task. Available energy or exergy concepts provide an analytic framework based on quality of energy. Exergy of a thermodynamic system is the part of energy which is the maximum useful work that can be obtained from the system at a given state in a specified environment and therefore, has economic value and is worth managing carefully. One of the main objectives of the exergy analysis is to locate and characterize the causes of exergy destruction or exergy losses, as well as to quantify the corresponding rates. As known, exergy analysis evaluates the available energy at different points in a system [26,27]. Bejan [2] pointed out that the minimization of lost work (i.e. exergy destruction) in the system would provide the most

efficient system. It has also been emphasized that the effect of operating conditions on the system efficiency is much stronger for lost work analysis than it is for the heat balance analysis. This explanation is required to determine the inefficient process, subsystem of the equipment, or operating procedure.

In brief, it can be said that exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design, optimization and improvement of the energy systems. Exergy analysis is used to complement not to substitute the energy analysis [28].

The exergy balance for steady flow process of an open system [25] is given by.

$$\sum \boldsymbol{E_{X_i}} + \sum \boldsymbol{E_X}^{\mathbf{Q}} = \sum \boldsymbol{E_{X_o}} + \boldsymbol{E_{X_W}} + \boldsymbol{IR\ or\ E_{X_d}} \tag{3}$$

where, $\boldsymbol{E_{X_i}}$ and $\boldsymbol{E_{X_o}}$ are the exergy associated with mass entering and leaving the system, respectively. $\boldsymbol{E_X}^{\mathbf{Q}}$ is the exergy due to heat transfer, $\boldsymbol{E_{X_W}}$ is the exergy due to work transfer and $IR\ or\ \boldsymbol{E_{X_d}}$ is exergy destruction due to irreversibilities within the system during the process.

The exergy ($\boldsymbol{E_X}^{\mathbf{Q}}$) transfer accompanying heat ($\boldsymbol{Q}$) from the system at temperature ($\boldsymbol{T}$) and environment at temperature, T_0 is determined from maximum possible rate of conversion of thermal energy into maximum possible work ($\boldsymbol{W}_{\mathbf{max}}$).

$$\boldsymbol{E_X}^{\mathbf{Q}} = \boldsymbol{W_{max}} = \boldsymbol{Q}\left(1 - \frac{\boldsymbol{T}_0}{\boldsymbol{T}}\right) \tag{4}$$

Energy is always conserved, exergy is not generally conserved, but it is destroyed by irreversibility (IR). For steady flow process, IR is given by

$$\text{IR or } \boldsymbol{E_{X_d}} = \boldsymbol{W_{max}} - \boldsymbol{W_{actual}} = \boldsymbol{W_{lost}} \tag{5}$$

This quantity represents an increase in unavailable energy or anergy. The Goudy- Stodola theorem states that the rate of loss of available energy or exergy in a process ($\dot{\boldsymbol{I}}$) is proportional to the rate of entropy generation, $\dot{\boldsymbol{S}}_{\boldsymbol{gen}}$

$$\dot{\boldsymbol{I}} = \dot{\boldsymbol{W}}_{\boldsymbol{lost}} = \boldsymbol{T}_o\, \Delta \dot{\boldsymbol{S}}_{\boldsymbol{univ}} = \boldsymbol{T}_o\, \dot{\boldsymbol{S}}_{\boldsymbol{gen}} \tag{6}$$

It is clear from the above definition that the thermodynamically efficient process would involve minimum exergy loss with minimum rate of entropy generation.

Exergy efficiency of any process is a ratio of the exergy transfer rate associated with the output to the exergy transfer rate associated with the driving input [29]. Thus exergy or the second law efficiency is defined as

$$\begin{aligned} \eta_{ex} &= \frac{\text{Desired output}}{\text{Maximum possible output}} = \frac{\text{Exergy output}}{\text{Exergy input}} \\ &= 1 - \frac{\text{Exergy destruction or Irreversibilities}}{\text{Exergy input}} \end{aligned} \tag{7}$$

Exergetic efficiencies are useful for distinguishing means for utilization of energy resources that are thermodynamically effective from those that are less so. It can also be used to evaluate the effectiveness of engineering measures taken to improve the performance of a thermal system. This can be done by comparing the efficiency values determined before and after modifications have been made to show how much improvement has been achieved. The value of η_{ex} is generally less than unity even when $\eta_e = 1$ [26]. In case of solar energy systems, η_{ex} is very low compared to other energy systems as discussed in the next section.

3.3. Solar exergy

The thermal radiation from the sun is relatively rich in exergy [30].But the exergy efficiency of a solar thermal collector or system is low. Extensive review of the problems of radiation exergy is provided by Bejan [2]. Some clarifications regarding exergy of thermal radiation have been given by Petela [23]. Petela has assigned the reason of low efficiency of solar thermal devices to the impossibility of full absorption of the insolation. In his view, to obtain high quality energy, at high temperature, the absorbing surface has to be at high temperature, which produces a large loss of energy by emission from the surface. This factor influences both the energy and exergy efficiencies. The large exergy loss takes place in absorption of solar radiation by absorber surface at a temperature quite less than the temperature of the sun as a black body radiation source [31,32]. Another factor which makes the exergy efficiency lower than the energy efficiency of solar thermal devices is caused by the significant degradation of energy quality. The relatively high temperature (approx. 6000 K) of solar radiation is degraded to the relatively low temperature e.g. to the temperature of heated water, which is not much larger than the atmospheric temperature; temperature of drying crops, solar cooking temperature, temperature required for photosynthesis, etc.

In the present study, the Petela expression $\boldsymbol{\Psi} = [1 + (1/3)(\boldsymbol{T_o}/\boldsymbol{T_s})^4 - (4/3)(\boldsymbol{T_o}/\boldsymbol{T_s})]$ is used to calculate the exergy of solar radiation. Here, ψ represents the relative potential of maximum energy available from solar radiation energy [30–32]; it is also called exergy efficiency term. Here, T_o is the temperature (in Kelvin) of the atmosphere or environment and T_s is the temperature (in Kelvin) of the sun.

Exergy of solar radiation ($\boldsymbol{E_{X_{sun}}}$) is calculated by multiplying the energy of solar radiation ($\boldsymbol{G_s}$) by the Petela expression $\boldsymbol{\psi}$, i.e.

$$\boldsymbol{E_{X_{sun}}} = \boldsymbol{G_s A}\left[1 + \frac{1}{3}\left(\frac{\boldsymbol{T_o}}{\boldsymbol{T_s}}\right)^4 - \frac{4}{3}\left(\frac{\boldsymbol{T_o}}{\boldsymbol{T_s}}\right)\right] \tag{8}$$

where, A is the area of surface of the solar device on which the solar radiation is incident.

The expression for the instantaneous overall exergy efficiency of the solar distillation system can be written as the ratio of exergy output of solar still to the exergy of the solar radiation using Eqs. (7) and (8):

$$\boldsymbol{\eta_{ex}} = \frac{\text{Exergy output of } a \text{ solar still}}{\boldsymbol{G_s A}\left[1 + \frac{1}{3}\left(\frac{\boldsymbol{T_o}}{\boldsymbol{T_s}}\right)^4 - \frac{4}{3}\left(\frac{\boldsymbol{T_o}}{\boldsymbol{T_s}}\right)\right]} \tag{9}$$

4. Thermodynamic modeling for energy analysis of solar still

Solar distillation is a complex process involving heat and mass transfer. Solar still is the sole or main component of any solar distillation systems of the past and present. The basic concept of solar still operation and its thermodynamic model has been proposed by Lof [33] and Dunkle [34]. The model proposed at that time, provides a strong base for further improvement and research in this field even today. A large number of research papers are available on thermodynamic analysis of solar distillation systems based on energy analysis elsewhere in literature [16,20]. Basic equations related with energy analysis of solar stills are presented in this section for further reference and use.

It is an established fact that a solar still operates similar to the natural hydrological cycle of evaporation and condensation. The evaporated water condenses on the inner side of the glass cover and pure distillate is collected in the separate container. Evaporated water leaves all the impurities including heavy metals, microorganisms and salt in the basin. The solar still may be

divided into the main nine segments such as glass cover, saline water body, basin liner or collector, bottom with insulation, side walls or edges, feed water, distillate output, vapor leakage and the environment or atmosphere through which solar thermal energy interaction takes place internally and externally.

For the energy and exergy analyses of any solar distillation system, it is necessary to understand the various heat transfer modes and energy flow during the operation of solar stills. External and internal heat and mass transfer process which is finally responsible for the solar still productivity is inter-linked. Fig. 2 shows the major energy transfer mechanism in a single effect double slope basin type conventional solar still during operation. A small part of the solar radiation incident (Q_{solar}) on the glass cover gets reflected ($Q_{refl,c}$), part gets absorbed within the material of glass cover ($Q_{abs,c}$), and the rest (i.e. large part) is transmitted ($Q_{trans,c-b}$) into the solar still. A part of the transmitted energy reaching the combined body of saline water and basin liner, sometimes called collector is reflected ($Q_{refl,w\&b}$) from the basin liner -saline water (collector) and larger part of it is absorbed by the basin liner ($Q_{abs,\ basin}$). The energy absorbed by the basin liner is largely transferred to the saline water and stored by the water on account of change of sensible heat content of the saline water ($Q_{stored,w}$) inside the solar still and a small fraction of it is lost to the environment through base of the solar still by conduction ($Q_{environ}$) or loss through insulation. Energy transfer from the basin liner-saline water (collector) to glass cover occurs by evaporation-condensation ($Q_{evap.}$) in addition to convection ($Q_{conv,b-g.}$) and radiation ($Q_{rad,b-g}$). The heat of vaporization ($Q_{evap.}$) is absorbed by the glass cover after condensation of water vapor and formation of distillate take place. The objective of any solar still design is to maximize $Q_{evap.}$, as this is directly proportional to still productivity and minimize other energy transfer in terms of losses from basin, walls, vapor leakage, etc. Energy received by the glass cover and rejected to the environment is also accounted. Energy transfer by convection ($Q_{conv,b-g.}$), radiation ($Q_{rad,b-g}$) from basin liner-water surface and a part of the incident solar energy ($Q_{abs,c}$), are absorbed by the glass cover. The heat, therefore, absorbed by the glass cover is lost to the environment by convection ($Q_{conv,g-a}$), and radiation ($Q_{rad,g-a}$). Heat transfer terms in the following equations are considered as $q = Q/A$.

An ideal solar still is one with zero conductive heat losses and a saline water level shallow enough to allow one to assume negligible sensible heat stored in the saline water body as compared to the energy transferred to and from the saline water. Dunkle [34], Morse and Read [35] and Cooper [36] have studied the performance of such a solar still which consequently attained a steady state almost instantaneously corresponding to the existing conditions. A steady state mathematical modeling for energy analysis of solar still is described here in the following forms which have been taken as the base for research and development of solar distillation systems [37].

The instantaneous energy balance equation on the saline water body in the basin (and basin-liner itself), per unit area of basin, can be written as

$$(\tau_c \alpha_b) G_s = q_e + q_{r,b-g} + q_{c,b-g} + q_L + C_b \frac{dT_b}{dt} \tag{10}$$

where, G_s is the rate of incident solar energy on the horizontal surface of solar still per unit area and the value is obtained with direct measurement of solar radiation (W/m^2), α_b is absorptivity of water and basin liner, τ_c is the transmittance of the cover and the water film or droplets on its underside, q_L is the heat losses from the bottom and sides of the solar still, C_b is the heat capacity per unit area of the basin and water, and T_b is the temperature of basin. An energy balance on the glass cover, taking heat capacity and solar energy absorbed by it into account, can be written as

$$q_e + q_{r,b-g} + q_{c,b-g} + G_s \alpha_g = q_{c,g-a} + q_{r,g-a} + C_g \frac{dT_g}{dt} \tag{11}$$

where, α_g is the absorptivity of the glass cover, C_g is the heat capacity of glass cover, T_g is the glass temperature. Reflective losses from glass cover are not included in this equation as it does not play any role into evaporation and condensation of water.

4.1. Internal heat transfer

Dunkle [34] recommends that the terms, $q_{r,b-g}$ for radiation exchange between basin and glass cover and $q_{c,b-g}$ for the convection energy transfer from basin to the glass cover, be written as

$$q_{r,b-g} = 0.9\,\sigma (T_b{}^4 - T_g{}^4) \tag{12}$$

here, σ is the Stefan Boltzmann constant. For the basin type solar still with low tilt angle of glass cover, the basin and glass cover may be assumed as two parallel infinite plates. Hence, the shape factor is assumed to be equal to the emissivity of the water surface which is 0.9.

$$q_{c,b-g} = h_{c,b-g}(T_b - T_g) \tag{13}$$

where, $h_{c,b-g}$ is the convective heat transfer coefficient between the water surface and the glass cover and it is estimated by the following empirical relation suggested by Dunkle [34] and converted in SI units.

$$h_{c,b-g} = 0.884 \left[(T_b - T_g) + \left\{ \frac{(P_{wb} - P_{wg})}{268.9 \times 10^3 - P_{wb}} \right\} T_b \right]^{1/3} \tag{14}$$

where, P_{wb} and P_{wg} are the vapor pressures of water (N/m^2) in the basin at T_b and at the glass cover temperature, T_g (in Kelvin).

Evaporative heat transfer, q_e from water surface to glass cover, is not a linear function of the temperature difference between the water surface of basin and the glass cover. It can be calculated by the following expression [15]:

$$q_e = 16.273 \times 10^{-3} h_{c,b-g}(P_{wb} - P_{wg}) \tag{15}$$

4.2. External heat transfer

The external energy transfer through convection($q_{c,g-a}$), and radiation ($q_{r,g-a}$), heat losses from glass cover to the environment can be calculated from the following expressions:

$$q_{c,g-a} = h_{c,g-a}(T_g - T_a) \tag{16}$$

$$q_{r,g-a} = \varepsilon_g\,\sigma\,(T_g{}^4 - T_{sky}{}^4) \tag{17}$$

where, ε_g is the emissivity of the glass cover; T_{sky} is the average sky temperature, that can be assumed to be about 12 K below atmospheric temperature for practical purpose. And $h_{c,g-a}$, the convective heat transfer coefficient from glass cover to the environment and can be obtained from the following expression in which, V is the wind velocity.

$$h_{c,g-a} = 2.8 + 3.8\,V \tag{18}$$

Bottom and side losses from the solar still to the environment including ground loss can be calculated as

$$q_L = U_L(T_b - T_a) \tag{19}$$

where, U_L is the overall heat loss coefficient.

The theoretical instantaneous efficiency of a solar still at any time may be given by the following equation based on Eq. (2):

$$\eta_e = \frac{q_e}{G_s} \tag{20}$$

The instantaneous efficiency from experimental measurement is calculated as

$$\eta_e = \frac{(\dot{m}_w\, h_{fg})}{G_s\, A_s} \tag{21}$$

where, $\dot{m}_w$ is the rate of distillate output from the solar still, h_{fg} is the latent heat of vaporization and A_s is the area of the basin of solar still.

Tsilingiris [38] has observed that the Dunkle model, based on several simplified assumptions, is extensively used since the last four decades as a convenient and sufficiently accurate predictive tool for solar stills working under ordinary conditions fails under unusual operating conditions, mainly corresponding to higher average temperatures (approx. above 50 °C) leading to higher distillate yields. The influence of binary mixture thermo-physical properties in the analysis of complex transport phenomena occurring in solar stills has been studied. Various equations for heat transfer coefficient and other properties of water vapor mixture have been developed. It is reported that the variation in values of heat transfer coefficients is almost constant till 60 °C, thereafter these values change considerably. Dev et al. [39] have made a new approach to obtain the characteristic equations of a double slope passive solar still based on experimental observations. It has been concluded that non-linear characteristic curves are more accurate than linear characteristic curves for analyzing the performance, thermal testing and further design modifications.

Some objections have been raised about the predictive accuracy of the fundamental Dunkle′s model. A detailed comparison of six numerical models (with and without considering humid air properties) for the estimation of water production from a solar distillation device is presented by Ahsan et al. [40].

5. Thermodynamic modeling for exergy analysis of solar still

There is limited research works on energy and exergy analyses of solar distillation systems. A general overview about exergy efficiency of collector and evaporator-condenser component of a solar still is discussed by Kwatra [41]. The individual contribution of the two energy conversion processes within the solar still to its overall efficiency is explained with the help of interpretation of a theoretical thermodynamic model based on "availability". The exergy analysis of a solar multi-effect distillation system (SOL-14 plant) has been performed by Garcia-Rodriguez and Gomez-Camacho [42].

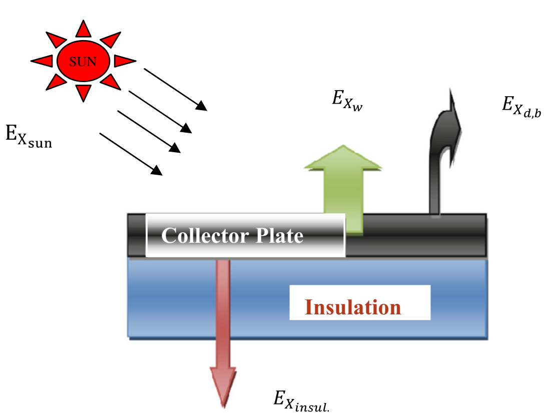

Fig. 5. Exergy flow diagram of the collector.

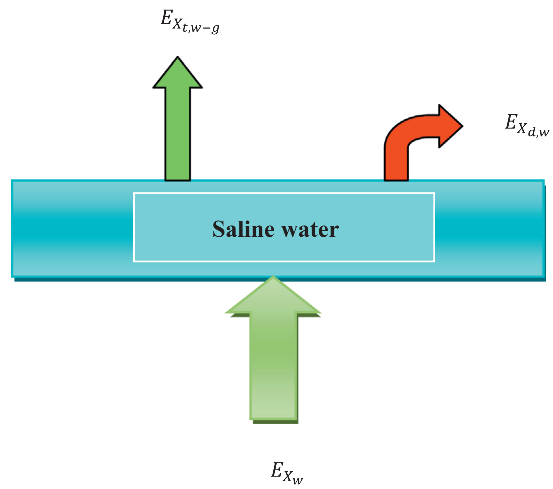

Fig. 6. Exergy flow diagram from saline water to the glass cover.

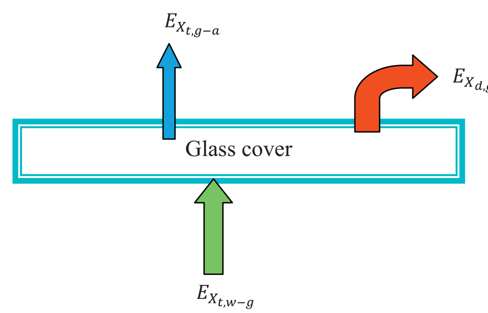

Fig. 7. Exergy flow diagram of the glass cover.

Energetic and exergetic analysis of a triple effect distiller driven by solar energy has been carried out by Sow et al. [43]. The exergetic efficiencies have been reported between 19% and 26% for a triple effect system, 17–20% for a double effect system, and less than 4% for a single effect system. The exergy analysis of a passive solar still is carried out by Torchia-Nunez et al. [44] and the model developed is worth to be mentioned here. The model to study solar distillation based on exergy analysis considered the following three main subsystems of a single effect single slope solar still as shown in Fig. 1.

a. The collector plate or basin-liner on which the saline water is kept and absorbs solar radiation.
b. The saline water (brine) to be evaporated.
c. The glass cover where water vapour condensates producing freshwater.

The basic concept of exergy of emission given by Petela [16] and the second law of thermodynamics defining exergy destruction and irreversibility [2,24,26,28] is the guiding principle in this analysis. Exergy flow mechanisms of the three subsystems are shown in Figs. 5–7. Exergy balance equations are given for the above three subsystems, as follows [44]:

Exergy destruction (Irreversibility) in the collector or basin-liner may be calculated considering the exergy flow through saline water body shown in Fig. 5:

$$E_{X_{d,b}} = \varepsilon_{col} E_{X_{sun}} - (E_{X_w} + E_{X_{insul.}}) \tag{22}$$

here, $(\varepsilon_{col} E_{X_{sun}})$ is the amount of the solar exergy $(E_{X_{sun}})$ absorbed in the collector, ε_{col} is the emissivity of the collector, E_{X_w} is the overall useful exergy transferred from the collector to the saline water body and consumed for heating and evaporation of the

saline water, and Ex_{insul} is the exergy loss through the insulation to the environment at T_o temperature.

The expressions for the exergy balances on the saline water according to Fig. 6 and the glass cover as per Fig. 7 may be expressed as,

$$Ex_{d,w} = Ex_w - Ex_{t,w-g} \tag{23}$$

$$Ex_{d,g} = Ex_{t,w-g} - Ex_{t,g-a} \tag{24}$$

here, $Ex_{t,w-g}$ is the sum of exergy associated with heat exchanges between the saline water surface and the glass cover similar to energy interactions in the form of free convection ($Ex_{c,w-g}$), evaporation ($Ex_{e,w-g}$), and radiation ($Ex_{r,w-g}$). $Ex_{t,g-a}$ represents the exergy losses from the glass cover to the environment by the process of radiation and convection.

Based on the values calculated as above, exergy efficiencies are calculated as

$$\eta_{ex,b} = \frac{Ex_w}{Ex_{sun}}, \quad \text{forexergyefficiencyofcollectororbasin-liner} \tag{25}$$

$$\eta_{ex,evap} = Ex_{e,w-g}/Ex_w, \quad \text{forexergyefficiencyofevaporationfromsalinewater} \tag{26}$$

In this analysis, Torchia-Nunez et al. [44] assumed that the glass cover produce no useful effect in distillation process neglecting the condensation process taking place inside the glass cover.

The exergy output of the solar still ($Ex_{e,w-g}$) is the exergy of heat associated with evaporation-condensation process leading to freshwater production and it may be calculated using Eq. (4). The exergy input to the solar still is the solar exergy calculated from Eq. (8). Thus, overall exergy efficiency of the solar still is evaluated using Eq. (9) similar to the expression given by Kaushik et al. [17].

$$\eta_{ex,overall} = \frac{Ex_{e,w-g}}{Ex_{sun}} = \frac{q_e\left(1-\frac{T_o}{T_w}\right)}{Ex_{sun}} \tag{27}$$

where, T_w is the temperature (in Kelvin) of water in the basin of solar still.

Finally, the expression for the global exergy efficiency [44] of the solar still may be written using Eq. (7) as:

$$\eta_{ex,\text{ solar still}} = 1 - \frac{(Ex_{d,b} + Ex_{d,w} + Ex_{d,g})}{Ex_{sun}} \tag{28}$$

Saidur et al. [45] have presented a brief review on the exergy analysis of solar energy applications in which some works on exergy analysis of solar multi effect humidification and dehumidification desalination process and solar powered membrane distillation are cited.

6. Observations of energy and exergy analysis: Theoretical and experimental

A number of thermodynamic analysis of the solar stills based on energy conservation have been reported in the literature. Observations of the most significant papers are highlighted in this section irrespective of its date of publication. Basic aim is to assess the progress in the areas of solar distillation systems with respect to productivity, energy and exergy efficiency; and the other factors responsible for the operation. Evidence of exergy analysis is newer and limited than that of energy analysis of solar stills. Malik et al. [15] has concluded that the radiation from the saline water surface to the cover is the largest single heat loss of 26% of the incident solar radiation. The heat loss resulting from reflection (11%) and absorption (5%) of solar radiation by the glass cover is also important. The ground and edge losses are only 2% and it is significant in this case as the base of the solar still is assumed not to be insulated during investigation. Re-evaporation of distillate and other unaccounted losses has been found 17%; the major part of this loss may be due to re-evaporation of distillate, nearly 10%. Garg and Mann [14] has carried out a detailed experimental investigation to find out the effect of climatic, operational and design parameters on the year round performance of single-sloped and double- sloped solar stills under Indian arid zone conditions. Findings of many theoretical analysis and observations of short duration presented by renowned scientists and researchers of the world such as Lof [33], Morse and Read [35], Cooper [36] and Soliman [46] have also been studied and compared by Garg and Mann [14]. The contradictory believes and observations about the effects of possible variations of the various parameters on the performance of solar stills during 60_s and 70_s have been clarified. the facts was later on agreed by the researchers worldwide with some improvement mentioned at the appropriate place in this article is worth to be mentioned here in detail as it will be helpful in understanding of the present and future works on the solar distillation systems. The salient features of the original finding of this investigation are as follows:

a. The long axis of the conventional double-sloped still should face an east-west direction in order to receive more solar radiation, particularly at high-latitude stations. A single-sloped solar still receive more radiation than a double-sloped solar still at low and high latitude stations.
b. The productivity of solar still increases with the increase of total solar radiation, ambient air temperature and wind speed. The productivity is unaffected by the vapor pressure of the atmospheric air.
c. In simple solar stills about 26% of the heat is lost through the base itself. The heat loss can be reduced by using insulation at the base. It was found through experiments that by increasing the thickness as well as quality of insulation and reducing the heat loss to minimum level, an improvement of about 7% in the distillate output could be obtained.
d. A lower inclination angle of glass cover gives higher productivity.
e. Both channels of the conventional double-sloped solar still, i.e. on the either side of the glass, collects the same amount of distilled water.
f. The productivity of a still increases with the decrease in water depth, increasing the absorptivity of water by using dyes and increasing the initial water temperature, i.e. by using the preheated water (active solar still).

The energy analysis carried out by Gomkale and Datta at Bhavnagar, India in 1976 on a double slope solar still having water depth of 2 cm and cover slope 20° from horizontal gives an idea about the quantity of energy flow, heat losses and consequently a scope for improvement. Only 38.4% solar energy has been utilized for evaporation and other heat losses have been found as heat loss by radiation (12.2%), heat loss by reflection from glass cover (10%), heat absorbed by cover (10%), heat loss by conduction through base (16%) and unaccounted heat loss (9.7%) such as vapor leakage, side losses, etc. The vapor losses may be negligible in small stills, but it has been observed that vapor leakage constitute an appreciable heat losses in large stills [47].

The maximum efficiency of single effect solar stills has been predicted by Cooper [48] first time through theoretical as well as experimental studies in 1973. It is observed that the theoretical maximum efficiency of an ideal single effect solar still can reach up to 60%. He also concluded about the experimental results that it is

highly unlikely: similar solar stills will attain efficiencies much greater than 50%. These findings are even today a guiding force for researchers and the article is worth to be referred. Samee et al. [49] reported that the energy efficiency and daily productivity of the simple basin type solar still are 30% and 3.1 L/m^2, respectively. It is also observed that the output of the still varies directly with the amount of solar radiation reaching on the still and the ambient temperature. The reported energy efficiency and distillate output per unit area of the solar still is found to be low in the range of 30–45% and with less than 5 L/m^2/day of fresh water production for most cases, even under optimized operating conditions [50].

There is much potential in solar energy conversion systems. Maximum conversion efficiencies for non-concentrating solar energy converters are found to be 50–77% of the incoming radiation energy, depending on atmospheric conditions [51]. Numerous researches have been done to improve the performance of solar stills and significant results have also been achieved. Goosen et al. [52] has studied a multieffect solar distillation system and found it more effective thermodynamically than a single effect solar distillation since the former uses the available heat energy more than once. The performance of a weir-type inclined solar still is studied by Sadineni et al. [53] and its daily productivity has been calculated as 5.5 L/m^2. Kabeel [54] studied the performance a solar still with a concave wick evaporation surface. The average daily distillate output and efficiency of the solar still: 4.1 L/m^2 and 30%, respectively, have been reported. Velmurugan et al. [55] studied the single basin solar still with the aim to improve productivity using fin, wick and sponge. 15.3%, 29% and 45.5% enhancement in productivity have been reported by the use of sponge, wick and fin, respectively. Rahin et al. [56] used different techniques to improve productivity of a horizontal solar desalination still. They separated the evaporating and condensing zones, used copper tube for condensing unit and water pumping on the black wall and also introduced a black aluminum plate as the basin liner in the base. The efficiency increased up to 31.1%.

Abu-Arabi et al. [57] have carried out a modeling and performance analysis of a solar desalination unit with double glass cover. It is concluded that by increasing the difference between the saline water temperature and temperature of glass cover, the productivity increases. Kumar and Tiwari [58] designed and fabricated a hybrid photovoltaic-thermal (PVT) active solar still and presented the experimental results. It is observed that the hybrid solar still of this kind gives a higher yield (more than 3.5 times) than the passive solar still. Abdallah and Badran [59] used a sun tracking system to improve still productivity. 22% enhancement of solar still productivity has been obtained. The effect of solar collector on the performance of solar still has been studied by Voropoulos [60]. It is observed that the productivity is doubled by the use of solar collector and storage tank. PCM storage medium is integrated with

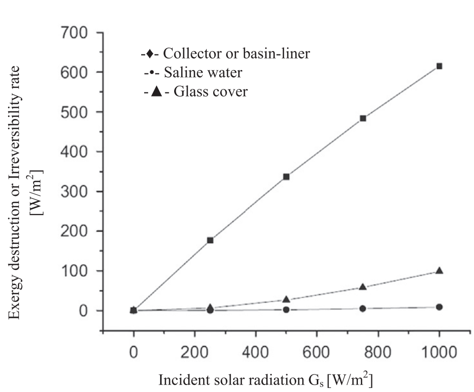

Fig. 8. Exergy destructions or irreversibilities of the collector or basin-liner, saline water and glass cover as a function of solar irradiance [44].

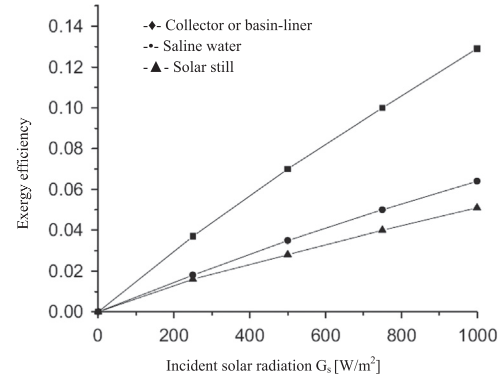

Fig. 9. Exergy efficiency of the collector, saline water and solar still (global) as a function of solar irradiance, G_S [44].

a single slope solar still for the study of thermal performance of the system by El-Sebaii et al. [61]. Their findings are very encouraging: after sunset, the storage medium acts as a heat source for the feed water of solar still until the next morning, consequently two times daily output of distillate with 84.3% efficiency is reported. Dev and Tiwari [62] have observed that the passive solar still with inclination of 45° gives better performance both in winter and summer. It is also shown that a lower water depth gives better efficiency, which is in agreement with many researchers.

Badran et al. [63] integrated a conventional flat plate solar collector with a solar still to increase the rate of distillate production. It is reported that the mass of distilled water production is increased by 52%, when the solar still is coupled with the solar collector. An experimental validation of thermal modeling of solar stills on the basis of heat transfer coefficients for summer and winter conditions has been suggested by Shukla and Sorayan [64] based on the basic energy analysis. It is found that the overall thermal efficiency of both single and double slope multiwick solar distillation systems in winter months is higher than summer months due to minimum heat loss at lower temperature. The double slope multiwick solar stills give a higher efficiency in summer due to more reflection losses in single slope multiwick solar stills. This observation including present exergy analysis may lead to better R&D activities in area of solar distillation systems.

Some of the findings of the exergy analysis of a passive solar still by Torchia-Nunez [44] are shown in Figs. 8 and 9. In these figures, dependence of irreversibility or exergy destruction rates and exergy efficiency on the solar irradiance, i.e. one of the main parameters of solar still is shown. Fig. 8 shows that as solar radiation increases, irreversibilities in the collector or basin-liner increase at a faster rate than irreversibilities in the glass and in the saline water (brine), in such a way that it can be neglected for glass cover and brine. It is widely known that these high values of irreversibility are due to the temperature difference between collector and the sun. Fig. 9 shows that for the same exergy input; exergy efficiency of 12.9%, 6%, and 5% are obtained for the collector, saline water and solar still, respectively. It is observed that the most influential parameter is solar irradiance. The largest exergy destruction is found to be in the collector (basin-liner), i.e. the greatest irreversibility rates of the whole system with approximately 80% of exergy input for a 1000 W/m^2 solar irradiance value. It is suggested that efforts should be directed towards better collector designs, still cover materials, evaporation- condensation studies and the reduction of collector-brine temperature gap.

Another model of energy and exergy analysis is presented by Tiwari et al. [65] for a passive and active solar distillation system in which the exergy output is estimated, i.e. exergy contained in the yield (distillate) of the solar still due to condensation of water.

Overall exergy efficiency of the solar still has been calculated. It has been observed from the results that the exergy efficiency is lower than energy efficiency. The effect of increasing the number of flat plate collectors in case of active solar distillation system has also been observed and found that both the energy and exergy efficiencies decreases due to more heat losses from the system. It is also shown that energy and exergy efficiencies decrease with increase in water depth.

The water evaporation area has received little attention as a design parameter. Kwatra [41] has presented a theoretical analysis of the effect of enlarged water evaporation area on the performance of the solar still. The performance of the collector and the evaporator- condensers are characterized by exergy efficiencies. This analysis showed that the efficiency of the collector initially increased as the evaporation area was enlarged but the asymptotic (infinite area) gain was around 1%. The analysis also suggested that solar stills with enlarged evaporation area could be operated on very low temperature thermal energy such as from solar ponds. The exergy efficiency defined for evaporator- condenser is shown to be useful in describing the performance of multiple effect solar stills as well. Kumar and Tiwari [66] have analyzed the energy and exergy efficiency of a shallow basin passive solar still. It is found that with decrease in absorptivity (from 0.9 to 0.6) with time, the energetic and exergetic efficiencies decrease by 21.8% and 36.7%, respectively. The effect of glass cover tilt is found to be insignificant and the respective efficiencies decrease by 0.75% and 0.47% per degree increase in tilt. These efficiencies increase rapidly up to a wind velocity of 2 m/s.

A thermodynamic model has been developed by Kaushik et al. [12] to estimate the overall instantaneous exergy efficiency of the single effect horizontal basin type ideal passive solar stills. The daily energy and exergy efficiency of the solar still is found to be 20.7 and 1.31%, respectively. A target of optimum exergy efficiency has been set under assumed typical conditions to achieve in the future for the real working passive solar stills. An optimum exergy efficiency of the ideal solar still is predicted as 21.11% corresponding to 80% ultimate energy efficiency (defined by Cooper [48]) and at a typical operating condition. It is concluded that there is much scope for improvement in the actual working solar stills as very less incident solar energy is being utilized. A lot of work is to be carried out in this regard under the present status of researches going on in the field of solar distillations. Energy as well as exergy losses of thermal energy are to be minimized through optimization of design and other influential parameters. It is desirable and necessary to find out the ways and means of reducing the cost of drinking water produced through solar distillation systems. One of the solutions lies in the efforts to examine the ways of maximizing the efficiency with the help of energy and exergy analysis [12].

Various means suggested for increasing the efficiency and productivity of the solar distillation systems increases the cost of desalination of saline water. Therefore, it is necessary to evaluate the unit cost of desalination of water through the solar distillation systems to decide the economic feasibility of the technically feasible system.

7. Thermo-economic analysis

Thermo-economic analysis is the technique which combines exergy analysis and economic principles to design and operate any cost effective system in larger perspective than the conventional energy and economic analyses. It may be considered as exergy based cost minimization tool for the thermal systems. Some literatures also term it exergoeconomic analysis. By this method, the thermodynamic inefficiencies of the system: exergy destruction and exergy losses and cost associated with such inefficiencies are evaluated. This approach is referred as exergy costing, in which a cost is associated with each exergy stream. Understanding of these cost is very useful for improving the cost effectiveness of the system and finally, for reducing the cost of the final product of the system under consideration [28].

Many investigations on thermal power plants, cogeneration and other energy systems using the thermo-economic analysis tool are reported in literature. It has been proved very useful in optimizing the entire system or specific variables in a single component. Basic equations for thermo-economic analysis of these systems are available elsewhere [67–69]. Thermo-economic analyses of desalination or other solar energy systems are scant in literature. Laranci et al. [70] have developed software 'SOLAR 1.1′ with purpose of helping the choice of photovoltaic panels available commercially including electric needs calculation for the installation. It also helps to conduct the economic analysis for grid connected or stand alone photovoltaic systems for the choice of convenient values of interest rate and payback period. For these evaluations, exergoeconomic modeling is used. This software has been successfully applied in various applications [71,72]. Similar studies can be carried out for the selection of the type of solar distillation systems economically feasible at a particular location based on various technical and economical parameters. But to the best knowledge of the authors of the present paper, there are no previously published results of thermo-economic analysis of solar distillation systems. However, there is need to know the thermodynamic inefficiencies cost, as it is very useful for improving the cost effectiveness of the solar still. It will help in reducing the cost of the system and eventually the cost of drinking water produced by the solar distillation system.

Energy cost is one of the most important elements in determining the water cost where the freshwater is produced from desalination plants based on conventional sources of energy. However, scenario is different in case of solar distillation system in which major items of cost comprises of capital investment, maintenance cost and the cost of supplying saline water to the distillation system, as solar energy is freely available. The capital investment depends upon system size including material and labor cost. The labor cost is highly variable and depends on the region. The system size depends upon the factors such as efficiency of solar energy utilization at various stages, thermodynamic inefficiencies, availability of solar energy, etc.

Techno-economic and economic analysis of solar desalination plants have been reported by some scientists and researchers. It has been felt that even a general economic analysis is not easy to carry out since only few studies report on the price of water or focus on economics of solar distillation. There are scant data available to compare construction costs, life of solar distillation systems and performance. The analysis becomes even more difficult due to the fact that most of the solar stills are constructed from local materials using local workers. The designs, the price of materials and labor charges varies from one location to another. Delyannis and Delyannis [73] have presented 'Economics of Solar Stills′ at the symposium on Economics of Water Desalination Processes. It has been emphasized that the solar distillation has a considerable economic advantage over other small distillation processes because of cost free solar energy, reduced operating costs and simplicity of system design, as no moving parts are involved. Hoffman [74] presented a detailed theoretical cost analysis based on operation data for solar driven desalination plants. He observed that the price of water from solar powered desalination plants varied from US$ 0.52 to 1.59/m^3.

Economic analyses of various designs of conventional solar stills: a single-slope fibre-reinforced plastic (FRP) still, a double-slope FRP still and a double-slope concrete still have been presented by Mukherjee and Tiwari [75]. The lifespan of the FRP still is assumed

10 years and that of the concrete still, 20 years. The various costs involved are at the level of Indian economy in the year 1985 when US $ 1.00 was equivalent to about Rs. (INR) 13.00. It was found that the minimum cost of distilled water produced from a conventional solar still was Rs. 0.15 /L. It has also been recommended that the FRP system should be used instead of the galvanized iron sheet body stills as it is easier to handle and the cost of distilled water production is lower. For the large scale solar distillation plants, the roof-type concrete still is the best. Techno-economic analysis of a multi-stage stacked tray (MSST) solar still is carried out by Adhikari et al. [76]. They presented a detailed model for techno-economic analysis. In this study, cost of the unit mass of distilled water has been taken as the optimizing economic parameters and all the results are presented in its form. Goosen et al. [77] has pointed out that the increase in efficiency of solar distillation systems by coupling it with the flat plate collector and other such components must be balanced against the increase in capital and operating costs when compared to a simple single basin type solar still.

An energy, exergy and life cycle cost analysis of single and double slope solar stills has been carried out by Dwivedi and Tiwari [78]. It is reported that double slope solar still gives higher distillate output in summer with low annual distillate, higher exergy efficiency, low cost of production and low energy payback time as compared to single slope solar still. Kumar and Tiwari [79] have reported the life cycle cost analysis of the single slope passive and hybrid photovoltaic (PVT) active solar stills. Taking into account the effects of various parameters, the comparative cost of distilled water produced from passive solar still {Rs.(INR) 0.70 /kg} is found to be less than hybrid PVT active solar still {Rs.(INR) 1.93/kg} for 30 years life time of the systems. Kabeel et al. [80] has reviewed the works on economic analysis of solar stills and estimated the water production cost of solar stills of 17 different design configurations. It has been concluded that the best average and maximum daily productivity are obtained from solar stills of single slope and pyramid shaped. The higher average annual productivity for a solar still is about 1533 L/m^2 using pyramid shaped while the lower average annual productivity is about 250 L/m^2 using modified solar stills with sun tracking. The lowest cost of distilled water obtained from the pyramid shaped solar still is estimated as 0.0135 $/L while the highest cost from the modified solar still with sun tracking is estimated as 0.23 $/L. A comprehensive review of all the indirect solar desalination technologies along with technical details of plants has been reported by Ali et al. [81]. The economic feasibility and cost affecting parameters for each desalination technology are also reviewed in the article.

The usual economic analysis model has been modified by incorporating the factor of equivalent cost of environmental degradation and high grade energy savings for solar stills by Ranjan and Kaushik [82]. The unit cost of desalination of saline water is estimated to be US$ 0.034/L corresponding to 30.42% energy efficiency of a passive solar still. It decreases to US$ 0.024/L using modified model. Due to higher capital cost of active solar stills, the unit cost of desalination of saline water is higher even if productivity is more. Effects of variation of energy efficiency, useful life, capital cost, etc are also studied. It is observed that prediction of the variation of unit cost of desalination of saline water with the variation of energy or exergy efficiency of a passive solar still is not simple. It is a complex matter of optimization of many parameters such as design parameters, capital cost, useful life, etc. Authors have tried to establish a relation between the increasing energy efficiency and reducing unit cost of desalination of saline water in ideal situation of constant capital cost at base value of design parameters as shown in Fig. 10. It shows that by increasing daily average energy efficiency from 10% to 60%, daily yield rises and consequently the unit cost of desalination of saline water reduces from US$ 0.103 to 0.017/L. The payback periods of the passive solar still are found to be in the range of 1.1 to 7.6 years if the selling price of distilled water decreases from US$ 0.18 to 0.04/L. The salient equations required for the usual economic analysis of the passive solar still adopted by Ranjan and Kaushik [82] are reported here which may be used for any solar distillation systems.

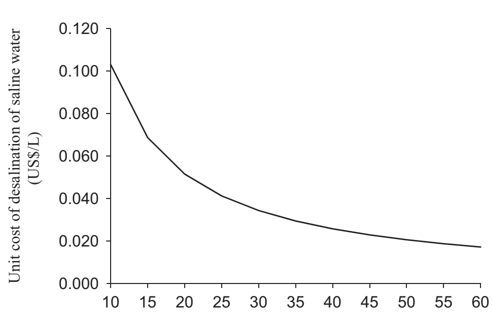

Fig. 10. Variation of the unit cost of drinking water with respect to the energy efficiency of the passive solar still [82].

The unit cost of desalination of saline water ($\boldsymbol{C_{dw}}$) is the ratio of total annualized cost of the solar still per unit area and average annual productivity in litres of the solar still per unit area ($\boldsymbol{M_{yearly}}$). Hence,

$$\boldsymbol{C_{dw}} = \frac{\text{Total annualised cost (TAC) of the solar still}}{\boldsymbol{M_{yearly}}} \tag{29}$$

where,

$$\boldsymbol{TAC} = \boldsymbol{AC_s} + \boldsymbol{OMC} - \boldsymbol{ASV} \tag{30}$$

The annualized capital cost of solar still ($\boldsymbol{AC_s}$) is calculated as the product of the present capital cost ($\boldsymbol{C_s}$) and $\boldsymbol{CRF}$:

$$\boldsymbol{AC_s} = \boldsymbol{C_s} \times (\boldsymbol{CRF}) \tag{31}$$

The Capital Recovery Factor ($\boldsymbol{CRF}$) is calculated as,

$$\boldsymbol{CRF} = \frac{i\,(1+\boldsymbol{i})^{\boldsymbol{n}}}{[(1+\boldsymbol{i})^{\boldsymbol{n}} - 1]} \tag{32}$$

where, $\boldsymbol{i}$ and $\boldsymbol{n}$ are the interest rate on annual basis and expected useful life of solar still in years, respectively.

Annual operation & maintenance cost (OMC) includes the annual cost involved in regular cleaning of the glass cover, removal of scaling due to salt deposition on the basin-liner and side walls, regular filling of saline water to maintain the level of saline water in the basin, and safe collection of distilled water regularly to avoid contamination.

Since annualized salvage value ($\boldsymbol{ASV}$) is the product of salvage value of solar still in future and the sinking fund factor ($\boldsymbol{SFF}$). It is expressed as,

$$\boldsymbol{ASV} = \boldsymbol{S} \times (\boldsymbol{SFF}) \tag{33}$$

where, S is the salvage value of solar still in future, and $\boldsymbol{SFF} = \left(\boldsymbol{i}/\left[(1+\boldsymbol{i})^{\boldsymbol{n}} - 1\right]\right)$

8. Latest scientific research based on solar energy utilization for desalination

The applications of solar energy is not only limited to distributed solar power generation but it has also gained popularity to fulfill many basic need like desalination, cooling, heating, cooking, drying etc. It promotes employment to local people and provides opportunity of social and economic development. It is well

established that there is strong potential of solar thermal energy to desalinate larger volume of seawater at larger scale but the processes are not much accepted at commercial level (with some exceptions) due to higher production cost as compared to conventional thermal distillation and reverse osmosis (RO) desalination technologies. A need to further improve the energy efficiency of desalination plants in addition to the existing techniques of active solar distillation systems has been felt among research communities. Many scientists are vigorously working to develop cost effective desalination system based on solar energy to compete with the desalination technologies operating with conventional sources of energy.

Garcia-Rodriguez and Delgado-Torres [83] have presented a preliminary analysis of distributed shaft power generation system based on solar-heated Rankine cycles for driving a reverse osmosis desalination process. It has been found that desalination system of this kind exhibit lower specific consumption of solar energy than solar distillation and solar photovoltaic RO systems. This fact shows an interesting prospect for developing cost-effective solar desalination system. Sharaf et al. [84] have suggested two different combined solar organic cycles with different configurations of multi-effect distillation (MED) processes. In the first technique, the solar energy is directly utilized from the solar collector field via evaporator heat exchanger to the first effect of the MED process producing only potable water. The second technique produces electricity with the help of the Organic Rankine cycle (ORC) turbine and the exhausted energy from the turbine is reused in the MED process producing potable water. In this analysis, they have used the tool of exergy and thermo-economic analyses to find out the true magnitude and location of exergy destructions and for comparisons of different configurations.

Gomri [85] has made an attempt to study the combination of flat plate solar collectors (FPC), a single effect heat transformer, and desalination system (distillation process) for seawater desalination. Solar thermal energy has been used as heat input for the heat transformer, which is a device for delivering heat at higher temperature than the temperature of the feeding fluid. The high grade thermal energy delivered by the heat transformer is utilized as heat source for water desalination. The energy and exergy analyses are carried out for each component of the system with the help of a computer program. It has been found that both the energy and exergy efficiency of FPC increases gradually until midday (approx. maximum value of 53% and 1%, respectively) then decreases gradually till the end of operation hour at 04.00 PM. The highest exergy loss has been found in FPC; however, the exergy loss is very small in the other components of the overall system compared to the exergy loss of FPC. Consequently, an overall thermal efficiency of 62% is obtained.

A few research works are being carried out to reduce the size and weight of solar stills without affecting the performance. A compact multiple effect diffusion type solar still comprising of a heat-pipe solar collector and a number of vertical and parallel partitions with saline soaked wicks has been designed by Tanaka and Nakatake [86]. This multiple-effect diffusion (MED)-type solar distillation system is designed in such a manner that it can be separated or folded as per requirement during shifting or transportation. The productivity of the proposed system is 13% higher than that of the VMED still coupled with a basin type solar still. El-Sebaii et al. [87] have attempted to improve the daily productivity of the single effect passive solar stills. The passive solar still is integrated with a shallow solar pond (SSP) for solar distillation at a relatively high temperature. The annual average values of the daily productivity and efficiency of the still integrated with the SSP were found to be higher than those obtained without the SSP by 52.36% and 43.80%, respectively. Esfahani et al. [88] has proposed a new and simple design method, and fabricated a portable solar still. A solar collector, walls made from Plexiglas and black wool, and water sprinkling system to increase evaporation rate and a thermoelectric cooling device to enhance condensation, are used to make the experimental set up. By increasing temperature difference between evaporating and condensing zone in this way, good efforts have been made to increase the productivity on a portable solar still. The average daily productivity of the still has been found 1.2 L/m^2 with maximum instantaneous efficiency of 13% in winter. Results show that this type of still has a reasonable production cost (0.13 \$/L/m^2) as compared to others.

In search of low-capacity solar thermal desalination units, Kabeel and El-Said [89] have reviewed the numerous works reported recently in literature and observed that the standard high-capacity desalination methods such as multi-stage flash evaporation and multi-effect evaporation, vapour compression and reverse osmosis are reliable in the range of about 100–500,000 m^3/day fresh-water productions. They have reviewed various low-capacity solar thermal desalination systems, with fresh-water output production in the range of 10–150 L/day for the use in rural areas. The solar thermal desalination systems are found to produce significantly higher distilled water output at lower cost through technological advancement and hybridization of systems compared with the conventional solar still under the same operational conditions. A new approach to enhance the productivity of a solar still by introducing an additional basin in the double slope solar still is attempted by Rajaseenivasan et al. [90]. Maximum productivity has been found to be 5.68 L/m^2/day for double basin solar still.

Rajaseenivasan et al. [91] have presented review of the different methods tried by different researches to improve the productivity of multi-effect and multi-basin passive as well as active solar stills. Productivity increases by the use of multi effect solar still due to utilization of latent heat energy with additional benefit of cost savings. Integration of flat-plate or parabolic collectors with multi-effect solar stills are found to give better yields. Singh et al. [92] have developed a thermal model to predict the performance of a solar still integrated with evacuated tube collector (ETC) in natural circulation. It is reported that natural circulation rate increases up to 44 kg/h in an individual tube when the radiation is at its peak and at high basin water temperature (80.0 °C). The integration of ETC with solar still increases the water temperature as well as productivity. The daily productivity is estimated to be 3.8 kg/m^2 for 0.03 m basin water depth. The productivity decreases further with increase in water depth. The variation of instant overall energy efficiency of the system has been found in the range of 5.1–54.4%, while exergy efficiency in the range of 0.15–8.25% between 9:00 AM and 03:00 PM. The maximum daily energy and exergy efficiencies have been found to be as 33.0% and 2.5%, respectively.

Most of popular heat and mass transfer correlations related with solar stills in literatures are summarized and evaluated by Gang et al. [93]. Neatly drawn schematics of the following different combination of solar stills proposed by researchers are presented in this study:

a. Basin solar stills with different glass covers,
b. Solar still with a vertical external reflector,
c. Active solar still coupled with a flat plate solar collector,
d. Active solar still coupled with a compound parabolic concentration (CPC),
e. Solar still coupled with a solar collector field,
f. Solar still with a separate condenser,
g. Solar still coupled with an outside condenser,
h. Floating tilted-wick type solar still,
i. Weir-type solar still,
j. Weir-type cascade solar still,

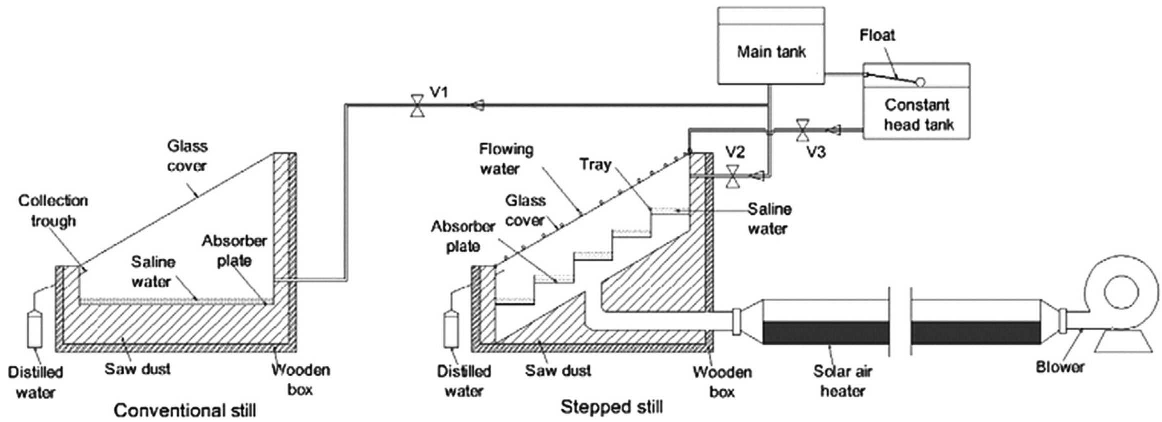

Fig. 11. Schematic of a single slope passive solar still and stepped active solar still integrated with a solar air-heater collector [94].

k. Vertical multiple-effect diffusion solar still coupled with a reflector,
l. Single basin solar still coupled with phase change material (PCM) storage.

Productivity and efficiency of the above solar distillation systems reported by the researchers are assessed with reference to designs and prevailing climatic conditions. Improvement in the productivity and efficiency through these designs encourage further R&D.

Recently, an experimental performance of a stepped solar still coupled with a solar air-heater is investigated by Abdullah [94]. A single slope passive solar still and stepped active solar still integrated with a solar air-heater collector were fabricated with an area of 0.5 m^2. In this set-up the hot air from the solar air heater is allowed to pass under the base of stepped still to heat the saline water and work in the active mode as shown in Fig. 11. Use of aluminum filling as thermal storage material beneath the absorber plate keeps the operating temperature of the solar still high enough to produce distillated water during the off- sunshine hours, particularly at night. Also, the effect of water flow over the glass cover and use of aluminum filling are also studied. Freshwater productivity of the integrated solar distillation system is found to be increased by 112% over conventional still.

9. Conclusions

Consumption of water and energy is compulsory for existence of human beings. Researchers are trying to find out the ways and means to meet the increasing demand of both water and energy without disturbing the ecology. Solar energy technology has been found a viable option among all renewable technologies that can be used for desalination on a scale ranging from small to large in remote rural as well as urban areas. The present ongoing R&D activities in the area of solar distillation systems have been presented in various sections of this paper. The thermodynamic models, theoretical and experimental results of the energy and exergy analysis of solar distillations systems are given. The following conclusions and recommendations can be highlighted:

a. Energy efficiency and productivity of the conventional solar stills is found to be low in the range of 20–46% and less than 6 L/m^2/day, respectively, for most cases, even under optimized operating conditions.
b. Productivity increases significantly by the use of multi effect solar still due to utilization of latent heat with additional benefit of cost savings. Integration of flat-plate or parabolic collectors with multi-effect solar stills are found to give better efficiency and yields.
c. The exergetic efficiencies have been found between 19% and 26% for a triple effect system, 17–20% for a double effect system, and less than 5% for a single effect system.
d. Overall energy and exergy efficiency of integrated system for solar distillation through single effect solar stills rises up to 62% and 8.5%, respectively.
e. Limited research works on the exergy analysis of solar distillation systems are reported in literature Extensive efforts has been made to improve the energy efficiency and productivity of the solar distillation systems based on the first law of thermodynamics taking into account of the heat and mass transfer phenomenon, but it is required to analyze the system based on exergy concept.
f. The cost of desalination through solar stills is estimated in the range of US$0.014 to 0.237/L. It decreases further with increase in efficiency.
g. It has been observed that the enhancement in efficiency of the solar still with proper modification in the system design having higher system cost finally increase the cost of the desalinated water. Reduction in the cost of desalinated water is possible by the optimum utilization of solar energy, reducing the size of system, design modification and reduction in the irreversibilities (exergy destruction) of the processes.

In the authors view, the worth of solar distillation systems for freshwater production should be evaluated beyond its technical and economical feasibility. Its capability to fulfill the requirement of freshwater supply where there is no other alternatives and potential of saving high grade energy being used for desalination through currently available devices in urban areas is of paramount importance.

Therefore, it is necessary to revive the solar distillation technologies with improved design of the system in the form of combination or integration of two or more solar devices for higher productivity and efficiency at competitive cost. It can contribute a lot to meet the increasing demand of freshwater and save high grade energy for sustainable development.

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